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NEUTRINO MASS AND MIXING, AND NON-ACCELERATOR EXPERIMENTS

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Abstract

We review the current status of experimental knowledge about neutrinos derived from kinematic mass measurements, neutrino oscillation searches at reactors and accelerators, solar neutrinos, atmospheric neutrinos, and single and double beta decay. The solar neutrino results yield fairly strong and consistent indications that neutrino oscillations are occurring. Other evidence for new physics is less consistent and convincing.

INTRODUCTION

Non-accelerator experiments have always played an important role in the physics of elementary particles, particularly the neutrino. Much of our early knowledge of the underlying symmetries that now are embodied in the Standard Model of Glashow, Salam, and Weinberg came from beta decay. The neutrinos continue to intrigue us because they seem to occupy an anomalous position in the Standard Model (lacking right-handed fields and, therefore, mass). Perhaps therein lies the road to the territory that we are convinced must lie beyond the Standard Model.

We focus our attention largely on experimental issues, and subdivide the review into sections that deal with kinematic mass measurements, neutrino oscillation searches at reactors and accelerators, solar neutrinos, atmospheric neutrinos, double beta decay, and 17 keV neutrinos. Proton decay is touched on only briefly. Topics such as theoretical issues, cosmological neutrinos, dark matter, gravitation, and non accelerator measurements of the Weinberg angle are covered by others at this conference (Krauss, Rolandi).

KINEMATIC MASS MEASUREMENTS

Figure 1 shows the experimental direct upper limits on the masses of the three flavors of neutrino as a function of time. With the exception of the ITEP result[1], no indication of non-zero mass has surfaced.

Tau Neutrino

The high mass of the τ makes a precision determination of the mass of ν_τ difficult, but also permits decays to multihadron final states. The Argus collaboration at DESY has observed[2] 12 decays to 5 pion final states, and a single such event with a mass close to that of the τ is sufficient to constrain severely the mass of ν_τ. An upper limit of 35 MeV at 95% confidence level (CL) has been established in this way. A further 8 decays have been seen, as reported at this conference,[3] but none is very close to the endpoint. However, three new measurements[4] of the τ mass have now

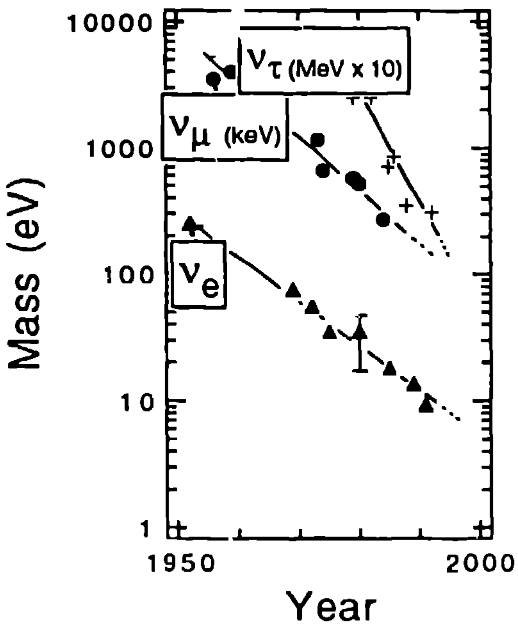

Figure 1. Experimental upper limits on neutrino mass.

Table 1. Mass of τ

Collaboration	Mass, MeV
Particle Data Group	$1784.1^{+2.7}_{-3.6}$
Beijing Spectrometer	$1776.9 \pm 0.4 \pm 0.3$
Argus	$1776.3 \pm 2.4 \pm 1.4$
CLEO II	$1777.6 \pm 0.9 \pm 1.5$

been reported, and these do result in a downward revision of the mass of ν_τ to 31 MeV (95% CL). The mass measurements are summarized in Table I.

The precision is still statistics limited, and with better resolution and higher statistics, one can look forward to sensitivity in the vicinity of 10 MeV. The only known direct approach to obtaining the mass of ν_τ (and ν_μ) at the level allowed by cosmology (tens of eV for stable neutrinos) is by observing a neutrino burst from a supernova.

Mu Neutrino

The tightest limit on the mass of ν_μ comes from measurements of the μ momentum following the decay of stopped pions. The most recent determination of the mass of the π^+ by Jeckelmann et al. coupled with the muon data of Abela et al. give

$$m_{\nu_\mu} \leq -0.097(72) \text{ MeV}^2,$$

which, with the Bayesian procedure described by the Particle Data Group,[5] yields an upper limit of 270 keV at 90% confidence on the mass of ν_μ.

A new round of experiments at the Paul Scherrer Institute has now reached such a high level of precision that a serious problem in this approach has been discovered. Table 2 gives the recent history of these measurements.

As indicated, the central value for m_ν^2 is over 5σ negative. The mass of the π^+ enters into the calculation, and has been deduced from pionic X-ray spectra. The precision is limited principally by theoretical uncertainties such as electron screening[10] and strong interaction effects (e.g. absorption from 3d state).

Stopped π decay is too subject to theoretical uncertainty to yield m_ν. Instead, it is perhaps the best way to determine m_π. What *can* we use for m_ν? Anderhub et al.[11] used a magnetic 'racetrack' and π decay in flight to obtain,

$$m_\nu^2 = -0.14(20) \text{ MeV}^2$$

$$m_\nu \lesssim 500 \text{ keV } (90\%\text{CL})$$

The method is (by design) relatively insensitive to m_π and m_μ, and, until some further progress is made on m_π, provides the best direct limit on the mass of m_ν.

Electron Neutrino

All modern determinations of the ν_e mass are searches for a distortion of the beta spectrum of tritium near the 18.6 keV endpoint. There are now 5 recent experiments, all of comparable precision, and all in good agreement (Table 3).

Table 2. Data on $\pi^+ \to \mu^+ + \nu_\mu$ at rest

Collaboration	Ref.	m_μ, MeV	p_μ, MeV/c	m_π, MeV	m_ν^2, MeV^2
Abela et al. 84	6	105.65932(29)	29.79139(83)	139.56761(77)	-0.163(80)
Jeckelmann et al. 88	7			139.56871(53)	-0.097(72)
PDG 88[a]	5	105.658387(34)		139.56737(33)	
Daum et al. 91	8		29.79206(68)	139.56996(67)	
Frosch et al. 92	9		29.79144(20)		-0.127(25)

[a] Electron mass down 8 ppm

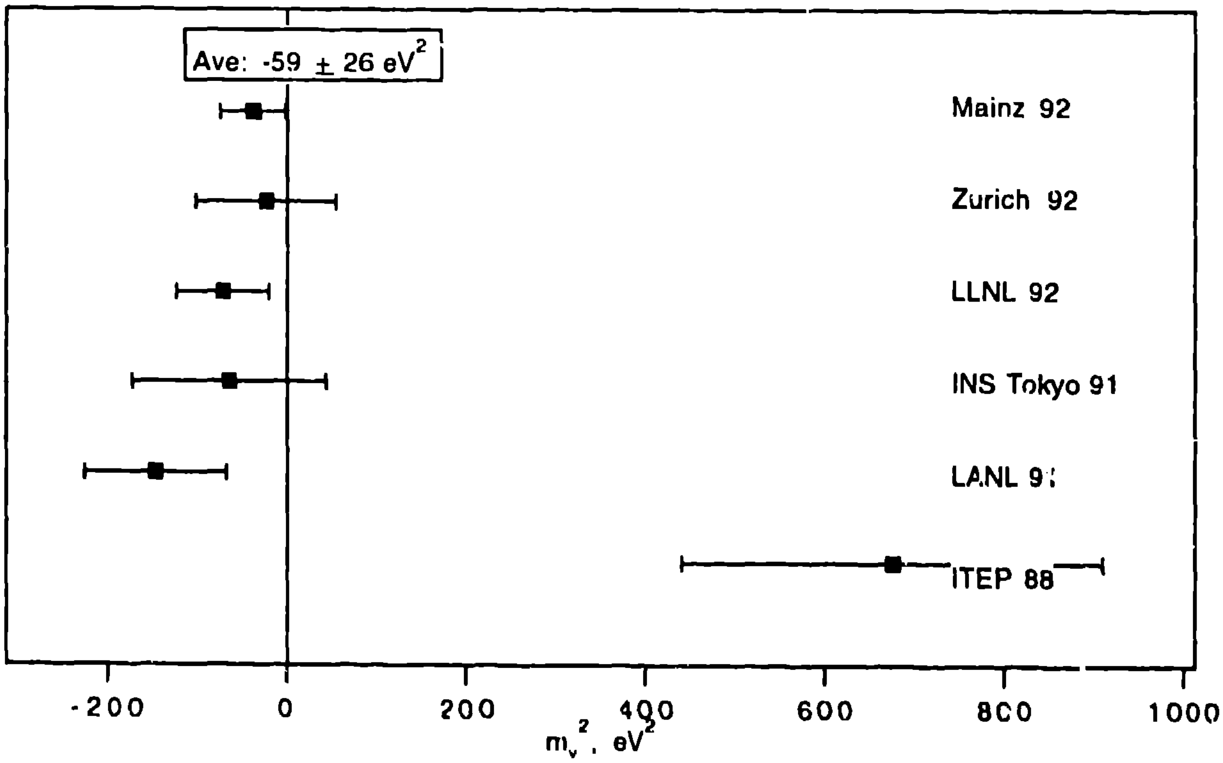

Figure 2. Recent determinations of the mass of $\bar{\nu}_e$ from tritium beta decay.

As both the Table and Figure 2 make particularly clear, the five experiments contradict the ITEP claim of a non zero neutrino mass, and it may now be safely concluded that that result is, for some reason, not correct.

However, it is striking that each of the five experiments yields a negative value for m_ν^2. A weighted average of the 5 gives

$$m_\nu^2 = -59 \pm 26 \text{ eV}^2,$$

which is 2.3 σ below 0, and represents only a 1.2% statistical chance (if m_ν is actually 0). If one proceeds nevertheless to find a Bayesian upper limit, it is 5 eV at 95% CL, but it must be emphasized that, with such a low probability, the limit is unsound.

The negative central value may be due to:

1. A statistical fluke.

2. A systematic error in the experiment. Some experimental systematic effect may be influencing one or more of the experiments. (Note that it need not be present in all of them simply moving one upwards by one to two standard deviations would result in a statisti

Table 3. Mass of $\overline{\nu}_e$

Institution	Ref.	Mass-squared MeV^2	Limit[a] eV
Los Alamos	12	$-147 \pm 68 \pm 41$	9.3
Livermore	13	$-75 \pm 41 \pm 30$	8.0
INS Tokyo	14	$-65 \pm 85 \pm 65$	13
U. Zürich	15	$-24 \pm 48 \pm 61$	11.5
U. Mainz	16	$-39 \pm 34 \pm 15$	7.2

[a]95% confidence level

cally unremarkable distribution.) However, the experiments do pass a necessary (although not sufficient) test for being systematic-free,[12] namely that the derived value for the ^{3}H-^{3}He mass difference agrees with independent determinations.

3. A systematic error in the theory. The negative result for m_ν^2 is a symptom of 'too many' counts near the endpoint. That could indicate the existence of an effect outside the conventional atomic and weak-interaction theories, and a number of exotic hypotheses have come to mind. They include a breakdown in the atomic physics calculations of the final-state spectra (particularly unlikely for the case of T_2), capture of relic neutrinos (there do not seem to be enough by at least 8 orders of magnitude), tachyonic neutrinos (theoretically unpalatable in concert with bradyon emission), and inner bremsstrahlung of a scalar or pseudoscalar particle that interacts only with neutrinos (e.g. a Majoron: this possibility is intriguing, but appears not to produce the required effect).

A 2.3 standard deviation effect is not sufficiently large to demand recourse to new physics, and for the moment the phenomenon remains unexplained. Further experimental work is needed to resolve the issue.

NEUTRINO OSCILLATIONS

We are entirely accustomed to the concept that mixing occurs in the quark sector; that is, the weak flavor eigenstates are not the same as the mass (strong-interaction) eigenstates, but are related by a unitary transformation **U**. It is very likely that, if neutrinos have mass, the same kind of mixing occurs. To search experimentally for such effects (forbidden in the Standard Model), one takes advantage of the fact that neutrino sources and detectors are 'flavor filters.' The probability that a neutrino mixture prepared in flavor λ is detectable in flavor λ' is

$$P_{\lambda\lambda'} = \sum_{kk'} U_{\lambda k} U_{\lambda k'} U_{\lambda' k} U_{\lambda' k'} cos(2.54 \Delta m^2_{k' k} \frac{L}{E}),$$

where

$$|\nu_\lambda > = \sum_k U_{\lambda k} |\nu_k >,$$

$$\lambda = e, \mu, \tau$$

$$k = 1, 2, 3.$$

The source-detector distance L is in m, the energy E in MeV and Δm^2 in eV^2.

Experiments with $\lambda = \lambda'$ are termed 'disappearance' and those for which $\lambda \neq \lambda'$ are 'appearance.' Owing to the need to determine the neutrino flux precisely, disappearance experiments tend to be limited in sensitivity to values of $P_{\lambda\lambda} < 0.95$.

For convenience, the experimental limits are usually presented in the context of two flavor mixing only, in which case the mixing matrix contains a single undetermined parameter, e.g. an angle, θ. This parameter and the unknown Δm^2 then define a two dimensional space in which experimental bounds can be placed but it should be remembered that nature may be more complicated.

Many groups have initially claimed evidence for oscillations, only to discover more mundane explanations for the effects seen. At present, there is no single experiment with reactor or accelerator neutrinos that indicates the presence of oscillations. (We will discuss atmospheric and solar neutrinos below.) An excellent, and still up-to-date, summary has been given by Boehm.[13] We supplement Boehm's review as follows:

1. Conforto[14] has drawn attention to a striking oscillatory behavior in the neutrino data from four high-energy fixed-target experiments. The results can mostly easily be interpreted as ν_e disappearance to a species other than ν_μ, with oscillation parameters:

$$\begin{aligned} \Delta m^2 &= 377 \text{ eV}^2, \\ \sin^2 2\theta &= 0.48 \pm 0.10 \pm 0.05. \end{aligned}$$

   These parameters are in conflict with the ν_e disappearance data from the Gösgen Reactor,[15]

$$\begin{aligned} \text{for } \Delta m^2 &\geq 5 \text{ eV}^2, \\ \sin^2 2\theta &\leq 0.22 \text{ (90\%CL)}, \end{aligned}$$

   as well as with the results of Fermilab experiment E531,[15] which yields,

$$\begin{aligned} \text{for } \Delta m^2 &\geq 100 \text{ eV}^2, \\ \sin^2 2\theta &\leq 0.18 \text{ (90\%CL)}. \end{aligned}$$

2. *A propos* of Conforto's observation, the Los Alamos tritium data is being analyzed for evidence of admixture of a neutrino of mass ~ 20 eV with the electron neutrino. Preliminary results disfavor the parameter set found by Conforto at about the 3σ level.

3. The CERN SPS Proposal P254 for direct searches for the interactions of ν neutrinos has been approved. The two experiments, 'Chorus' and 'Nomad' are expected to have sensitivities to $\nu_\mu \to \nu_\tau$ of order 3-4 x 10^{-4} in $\sin^2 2\theta$ for $\Delta m^2 \geq 50$ eV^2, and to $\nu_e \to \nu_\tau$ at the level of 2 x 10^{-2}.

4. New reactor-based experiments are being considered, in addition to the one[13] under construction at the San Onofre complex. A new reactor complex at Chooz in northern France may be the site of a 12-tonne, 1-km experiment,[16] and the fortunate location of the Morton salt mine 12 km from the Point Perry reactors in Ohio may be exploited.[17]

ATMOSPHERIC NEUTRINOS

The interaction of cosmic rays with the upper atmosphere produces showers of hadrons, mostly pions and kaons. The decay sequence

$$\pi^+ \to \mu^+ + \nu_\mu,$$
$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

together with the charge-conjugate reactions, leads to the naive expectation that the flux of μ-flavor neutrinos should be twice the flux of electron-flavor neutrinos. That raises the possibility of a neutrino-oscillation search based on a measurement of the ratio. With baselines ranging from 10 to 10,000 km and energies of 100 to 1000 MeV, a region of parameter space inaccessible to other techniques can be explored. More detailed flux calculations[18–23] take into account the effects of particles ranging out before decay, particles penetrating the earth's crust, directional correlations induced by kinematics and polarization, geomagnetic effects in the primary cosmic ray spectrum, and nuclear absorption of pions. While the absolute fluxes are uncertain at the level of perhaps a factor of 2, the flavor ratio is considered accurate to about 5% above 50 MeV.

Both the large water Čerenkov detectors, Kamiokande[24] and IMB,[25] find substantial departures from the expected flux ratio in the visible-energy range 100-1000 MeV. The Frejus[26] and NUSEX[27] experiments, with more limited statistics, find no evidence for the effect, but are not seriously in disagreement either. The results are expressed as the experimental flavor ratio divided by the ratio expected from Monte Carlo simulations based on the theory of neutrino production and absorption, and detector characteristics. They are summarized in Table 4.

Table 4. Atmospheric neutrino flavor ratios.

Collaboration	$\frac{\nu_\mu}{\nu_e}$ Data/$\frac{\nu_\mu}{\nu_e}$ M.C.
Kamiokande	$0.60^{+0.07}_{-0.06} \pm 0.05$
IMB-3	$0.54 \pm 0.05 \pm 0.12$
Frejus	$1.06 \pm 0.18 \pm 0.15$
	$0.87 \pm 0.16 \pm 0.08^a$
NUSEX	$0.99^{+0.35}_{-0.25} \pm ?$
IMB-3	$1.01 \pm 0.03 \pm 0.11^b$

^{a}Fully contained events

^{b}Stopping/through muons

If this anomalous ratio is due to $\nu_\mu - \nu_e$ oscillations, there is further information to be obtained on that possibility from upward-going muons. Such muons can only come from neutrino interactions in the rock surrounding the detector and the detector itself — cosmic ray muons themselves cannot penetrate that far. Owing to the larger fiducial mass of the 'target', such interactions are due to higher energy neutrinos that have travelled greater distances and therefore explore much the same region of oscillation space. Upward going muons that stop in the detector are produced mainly by 3 to 30 GeV ν_μ, while those that pass through are from 30 to 300 GeV ν_μ. From upward going muon rates, the IMB-3 collaboration has been able to rule out a significant part of the parameter space (last line of Table 4), particularly the regions containing the best-fit values. Figure 3 summarizes the data.

In order to conclude that neutrino oscillations are responsible for the anomaly, it is necessary to rule out more mundane explanations. Perhaps there are errors in the calculated flux ratio, or in the calculated cross sections for the interactions of ν_μ and ν_e with ^{16}O. Some of the cross section is contributed by free protons, for which the cross sections are well known,[19] but the main contribution is believed to be quasi-elastic interactions with neutrons and protons in oxygen. The rates are calculated in the framework of the Fermi Gas Model (FGM)[26] with "nuclear corrections" that, in essence, use non-interacting shell-model wavefunctions instead of plane waves. There is relatively little experimental information about these ingredients, but we note that recent work at LAMPF by Koetke et al.[27] on the $^{12}C(\nu_\mu, \mu^-)X$ reaction with neutrinos up to 300 MeV indicate poor agreement with the FGM. Figure 4 shows the results.

We remark that the momentum transferred to recoiling nucleons can be quite small, and that the FGM may be a particularly bad approximation in the part of the spectrum that is nearly elastic. The mass of the μ could then play an important role in suppressing the (ν_μ, μ) cross section.

Yet another explanation has recently been advanced by Mann et al.[28] They observe that it is not clear whether the atmospheric neutrino data indicate a deficiency of ν_μ or an excess of ν_e — the absolute fluxes are not well enough known. Taking the quasi elastic flux calculated by Bugaev and Naumov,[18] they find good agreement with the μ spectrum, but an excess of electron events that can be attributed to proton decay in the detector: $p \to e^+\nu\nu$. The partial lifetime of the proton against this mode is found to be 4 x 10^{31} y. If correct, this

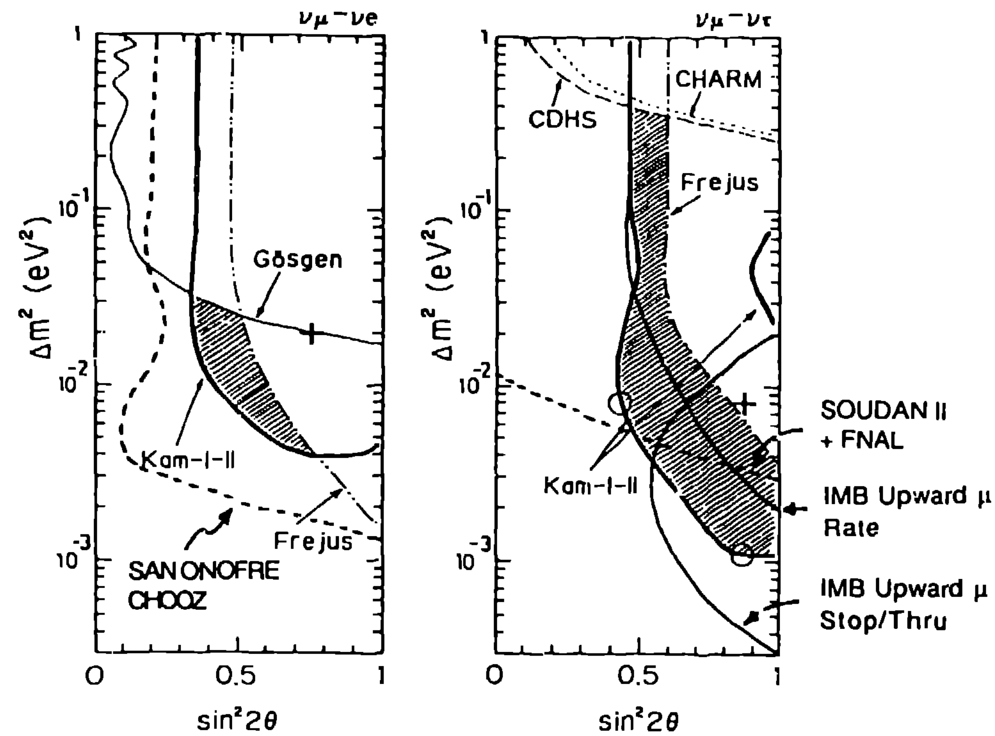

Figure 3. Oscillation parameters in the $\nu_\mu - \nu_e$ and ν_μ disappearance channels. The dotted lines indicate limits to be obtained from future experiments. The crosses are the best fit values from Kamiokande.[24]

would, of course, be a very exciting development.

SOLAR NEUTRINOS

The longstanding solar neutrino problem, which has been extensively reviewed,[29] may be a neutrino-oscillation experiment with a positive result. There are now 4 operating experiments, Homestake, Kamiokande, SAGE and Gallex, and 2 (Sudbury Neutrino Observatory and SuperKamiokande) under construction. Others are in the development phase. The experiments are listed in Table 5. All the operating experiments find lower measured fluxes than are predicted by the "Standard Solar Model" (SSM). It is a commonly held view that the flux of neutrinos from the Sun is hard to calculate — this is not the case. The total luminosity of the Sun is precisely measured, and, if nuclear fusion of H into He provides the energy, then exactly two neutrinos must be produced for each completion of a fusion cycle. Each cycle yields 26 MeV of energy, and (provided ^{8}B is not a major branch, which we know experimentally), at most a few percent of the energy is lost in neutrino emission. Hence the flux can be calculated. What is much more difficult to calculate, of course, is the energy spectrum, because that depends on all the details of nuclear cross-sections, opacities, heavy-element composition, turbulence, etc. The ^{8}B branch, a negligible contributor to energy production, is quite sensitive to the details, whereas the p-p flux is almost independent of them.

There are now two comparably detailed calculations of the solar neutrino spectrum, which are in good agreement when the same input parameters are used. That was not always so, and numerous small corrections and changes have been made to both computations on the way to convergence. The results are summarized in Table 6, with 1σ uncertainties.

The significant differences between the two calculations stem from the inclusion by Bahcall and Pinsonneault of helium diffusion,

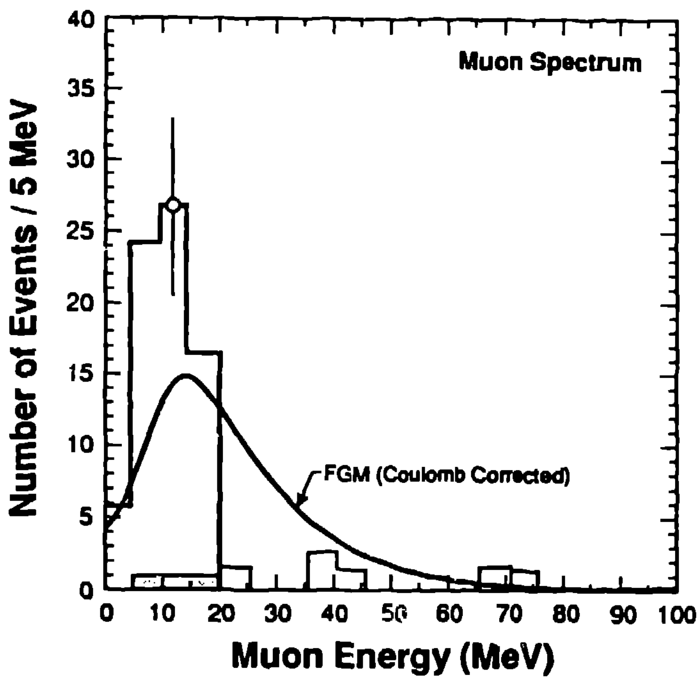

Figure 4. Data on $^{12}C(\nu_\mu, \mu^-)X$ (ref. 27) compared with the FGM

Table 6. Solar neutrino rate calculations.

Target	B-P[a]	T-C[b]
^{37}Cl	8.0(10)	6.4(14) SNU
e^- (H_2O)	5.7(1±0.15)	4.3(11) 10^6 cm^{-2}s^{-1}
^{71}Ga	132^{+7}_{-6}	123(7) SNU

[a]Ref. 30 [b]Ref. 31

which increases the ^{8}B flux by 12%, and a different choice of cross section for the ^{7}Be(p,γ)^{8}B reaction. The experimental results are summarized in Table 7.

The SAGE *collaboration announced* at this meeting[34] results from a second round of data-taking at Baksan. The 1990 and 1991 data sets give, respectively, $20^{+15}_{-20}\pm32$ and $85^{+22}_{-32}\pm20$ SNU, and a combined average as given in Table 7. The large systematic error in the first set was assigned to cover the possibility that the counter backgrounds increased with time, as indicated in a few runs. This effect was not seen in the next data set, and so is likely to have been a statistical fluctuation (not improbable with such low statistics). In the second data set, the systematic uncertainty was dominated by radon corrections, and the 'systematic' errors in the two runs are thus largely uncorrelated. The collaboration has applied the Kolmgorov-Cramer-von Mises tests to the data and find that the goodness-of-fit parameter N^2_ω for the combined data is 0.107, which would be exceeded 55% of the time. That indicates that all the data can have come from the same parent distribution. The probability that the early points would be mostly lower than the later ones is not addressed by this statistic, however. The Gallex collaboration does not provide information about goodness-of-fit. Taken at face value, the results of both experiments are in reasonable agreement, with a combined average of 74^{+16}_{-17} SNU. That is definitely not consistent with any SSM, but it falls in the grey area between astrophysical problems and neutrino physics problems. The minimum flux consistent with static hydrogen-burning in the Sun is about 79 SNU.

Table 5. Solar neutrino experiments.

Target	Collaboration	Status	Threshold (MeV) CC	NC	Fid. Mass (tonnes)
^{37}Cl	Homestake	'69-	0.814	-	615 C_2Cl_4
e^-	Kamiokande	'85-	7.5	7.5	680 H_2O
^{71}Ga	SAGE	'90-	0.233	-	30, 57 Ga
^{71}Ga	Gallex	'91-	0.233	-	30 Ga
^{2}H, e^-	SNO	'96-	5.0	2.2	1k D_2O
e^-	SuperKamiokande	'96-	7.5	7.5	22k H_2O
^{11}B, e^-	Borexino	Prop.	0.25	0.25	100 TMB
^{40}Ar, e^-	Icarus	Prop.	2	2	1k LAr
Plus ^{115}In, LHe, ^{205}Tl, Cl, F, I, ^{98}Mo, and others					

Table 7. Solar neutrino rate measurements.

Experiment	Target	Rate	% B-P[a]	% T-C[b]
Homestake[c]	^{37}Cl	2.25 ± 0.24 SNU	28 ± 3	35 ± 4
Kamiokande II & III[d]	e^- (H_2O)	$284 \pm 29 \pm 35 \times 10^4\ cm^{-2}s^{-1}$	50 ± 8	66 ± 11
SAGE I & II[e]	^{71}Ga	$58^{+17}_{-24} \pm 14$ SNU	44^{+17}_{-21}	47^{+19}_{-23}
Gallex[f]	^{71}Ga	$83 \pm 19 \pm 8$ SNU	63 ± 16	67 ± 17

[a]Ref. 30 [b]Ref. 31 [c]Ref. 32 [d]Ref. 33 [e]Ref. 34 [f]Ref. 35

Bludman et al.[36] have made a study of all the extant data except SAGE to learn if they force us to embrace new neutrino physics. They conclude that Mikheyev-Smirnov-Wolfenstein (MSW) matter-enhanced neutrino oscillations explain all the data very well, with the best fit values being

$$\Delta m^2 = (0.3 - 1.2) \times 10^{-5}\ eV^2$$

$$\sin^2 2\theta = (0.4 - 1.5) \times 10^{-2}.$$

A large-angle solution is also permitted but fits less well. [Inclusion of SAGE will drive Δm^2 down and $\sin^2 2\theta$ up by an amount roughly equal to the range.] Petcov and Krastev[37] have also pointed out that, even with only 2 flavors oscillating, a vacuum solution remains viable:

$$\Delta m^2 = (0.5 - 1.1) \times 10^{-10}\ eV^2,$$

$$\sin^2 2\theta \geq 0.75.$$

'Cool-Sun' explanations, in which the core temperature of the Sun is arbitrarily reduced, fail to account for the data: the fundamental conflict is between Homestake and Kamiokande, because they both record mainly the ^8B flux. Neutrino oscillations provide a much better account of the data because neutral-current scattering naturally increases the Kamiokande rate relative to the Cl-Ar rate. For the same reason, oscillation into sterile neutrinos is somewhat disfavored. The indications are strong that neutrino oscillations are indeed occurring, but the new generation of experiments SNO with its explicit neutral current and spectroscopic capabilities, SuperKamiokande with its large volume, and

Borexino with its low threshold – can provide the definitive proof.

DOUBLE BETA DECAY

Neutrinoless double beta decay enjoys a phase-space advantage over $\beta\beta\nu\nu$ emission (allowed in the Standard Model, but very slow), and searches for it set tight limits on the Majorana masses of electron neutrinos (or of the admixed mass eigenstates that comprise the electron neutrino). The best limits on the effective Majorana mass come from isotopically enriched ^{76}Ge detectors:[38,45]

$$< m_\nu > = \sum_i \xi_i U_{ei}^2 m_i \leq 2 \pm 1 \text{ eV}.$$

The uncertainties are mostly theoretical.

The allowed 2-neutrino mode has now been observed[39,40] in 4 isotopes: ^{76}Ge ^{82}Se, ^{100}Mo, ^{150}Nd, with halflives ranging from 8 to 920 x 10^{18} y (Table 8). Radiochemical experiments[41,42] have also demonstrated the occurrence of double beta decay in ^{130}Te and ^{238}U, although in those cases the mode is unknown. In each of the 4 cases measured spectroscopically, a few extra events have been seen in the region between the energy at which the 2ν distribution has effectively died away and the Q-value. Events are not forbidden there, but their probability is so low ($<10^{-5}$) that they may indicate a departure from the expected physics.

A third possible mode of double beta decay was discovered as a consequence of theories that explain the smallness of neutrino mass in terms of a spontaneously broken B-L symmetry that allows otherwise massless neutrinos to acquire a small Majorana mass.[43,44] A consequence of spontaneous symmetry breaking is the appearance of a massless Goldstone boson, in this case dubbed the 'Majoron.' The Majoron couples only to neutrinos and effectively flips the helicity of the virtual neutrino in neutrinoless double beta decay. The resulting 3-body phase space fits remarkable well with the anomalous 'hard' events observed experimentally. The intensity is 2-3 percent of the 2-neutrino intensity. At this conference Piepke[45] reported on the results from a large isotopic ^{76}Ge detector (Heidelberg-Moscow collaboration). With approximately 4000 2-neutrino decays observed, a small excess (150) is seen in the high-energy region, consistent with the other experiments. However, the shape at lower energies does not seem to fit the 'standard' Majoron hypothesis.

One can also derive limits on Majoron modes from the non-observation of certain decay modes of hadrons,[46] although experiments do not at present have enough sensitivity. Haxton[48] has used the ratio of experimental half-lives[41] for ^{128,130}Te to set an upper limit on the coupling constant $< g_M >$ of 4.2 x 10^{-5}. Finally, Burgess and Cline[47] have shown that 'standard' Majorons do not meet the requirements because the implied Majorana neutrino mass would allow 0ν decays, in contradiction to experiment. If the Majoron carries lepton number -2, then this difficulty can be circumvented. Note that the Burgess-Cline values for the coupling constant differ somewhat from those shown.

Needless to say, if the evidence for anomalous events continues to accumulate to the point where a Majoron of some type is confirmed, it will be a revolutionary development for particle physics. Great progress towards resolving the issue is being made by the experimental groups. The UC Irvine group have increased the magnetic field in their time projection chamber to improve the resolution and the capability for measuring it. Very low background isotopic Ge and Xe detectors are just beginning to accumulate data, with already impressive results.

Table 8. Double-beta-decay experiments (selection).

Isotope	Ref.	Q (MeV) MeV	$T^{2\nu}_{1/2}$ (y) 10^{18} y	$T^{0\nu}_{1/2}$ (y) 10^{23} y	$T^{0\nu M}_{1/2}$ (y) 10^{20} y	$< g_M >$ 10^{-4}
^{82}Se	39	2.995	108^{+26}_{-6}	-	11(4)	2.4(4)
^{100}Mo	39	3.034	$11.6^{+3.4}_{-0.8}$	-	1.5(6)	4.2(4)
^{150}Nd	39	3.367	8	-	0.8(5)	2.1(7)
^{76}Ge	40	2.039	920^{+70}_{-40}	-	200(-)	1.4(-)
^{76}Ge	45	2.039	-	>17 (90%CL)	>400	<1.1
^{130}Te	41	2.533	2670(90)	>0.03 (90%CL)	-	-
^{238}U	42	1.100	2100(600)	-	-	-
$K^+ \rightarrow l^+ \nu M$	46					<70

THE 17-keV NEUTRINO

The shape of the spectrum in ordinary beta decay has, since the earliest days, been used to set limits on the masses of neutrinos. Recently, many experimental groups have observed 'kinks' in the spectra of ^{3}H, ^{14}C, ^{35}S, ^{45}Ca, ^{63}Ni, and ^{71}Ge at an energy 17 keV below the endpoint, which can be interpreted as an admixture of a 17-keV neutrino with the electron neutrino at an intensity of approximately 1%. The striking uniformity of the results from a wide range of isotopes is illustrated in Fig. 5.

All the positive observations have made use of solid-state detectors. Searches made with magnetic devices have been uniformly negative. The experimental situation is summarized in Table 9. Criticisms have been levelled at both techniques. Bonvicini[illegible] recently made an exhaustive study of the interplay between statistical and systematic errors in 17-keV experiments and concluded that use of arbitrary shape correction parameters of Taylor-series form when the true underlying energy dependence of efficiency is unknown can be very dangerous. All magnetic spectrometer experiments have been obliged to do this, owing to the difficulties in determining the response to the necessary accuracy. It was therefore not clear that negative experiments really ruled out the purported effect at the claimed level. Piilonen and Abashian[50] drew attention to small effects due to scattering that were neglected in Si detector experiments and that could possibly induce spurious distortions resembling a massive neutrino.

The balance has now been strongly tipped against a 17-keV neutrino by two new experiments reported at this meeting. A group at the Institute for Nuclear Studies in Tokyo[77] carried out a magnetic-spectrometer study of ^{63}Ni with extremely high statistical precision (2.4×10^9 events in the interval 40-60 keV). While arbitrary shape-correction parameters (30 of them) are still required to fit the data (30 independent spectra acquired in three overlapping energy ranges), the overwhelming statistical precision essentially precludes a real 17-keV neutrino distortion from being concealed. The upper limit of 0.073% admixture at 95% CL does not take into account the possible systematic errors in the shape correction, but it is highly unlikely that such a good fit with such high statistics could conspire to conceal a 17 keV neutrino.

An experiment carried out at Argonne National Laboratory by Ahmad et al.[73] makes use

Table 9. Experiments on the 17-keV neutrino.

Collaboration	Ref.	Source	Method	m_ν, keV	$\sin^2 2\theta$
Simpson	51	T in Si	Crystal	17.1(2)	0.03
Haxton	52		Exchange Corrections		
Lindhard & Hansen	53		Screening Corrections		
Simpson (revised)	54,55	T in Si	Crystal	17.1(2)	0.011(3)
Altzitzoglou et al.	56	^{35}S	Magnetic		<0.004 99% CL
Ohi et al.	57	^{35}S	Crystal		<0.0015 90% CL
Apalikov et al.	58	^{35}S	Magnetic		<0.0017 90% CL
Datar et al.	59	^{35}S	Crystal		<0.006 90% CL
Markey & Boehm	60	^{35}S	Magnetic		<0.003 90% CL
Hetherington et al.	61	^{63}Ni	Magnetic		<0.003 90% CL
Hime & Simpson	54	T in Ge	Crystal	16.9(1)	0.011(5)
Simpson & Hime	62	^{35}S	Crystal	16.9(4)	0.0073(9,6)
Hime & Jelley	63	^{35}S	Crystal	17.2(5)	0.0085(6,5)
Sur et al.	64	^{14}C	Crystal	17.1(6)	0.012(3)
Becker et al.	65	^{35}S	Magnetic		<0.006 90% CL
Zlimen et al.	66	^{71}Ge (IB)	Crystal	17.2(12)	0.016(7)
Schonert et al.	67	^{177}Lu	Magnetic		<0.004 68% CL
Hime & Jelley	68	^{63}Ni	Crystal	16.8(4)	0.0099(12,18)
diGregorio et al.	69	^{71}Ge (IB)	Crystal	13.8(18)	0.0080(25)
Bahran & Kalbfleisch	70	T_2 gas	Prop. Ctr.		<0.004 98% CL
Hargrove et al.	71	T_2 gas	Prop. Ctr.		(in progress)
Wark	72	^{35}S	Magnetic		(in progress)
Ahmad et al.	73	^{35}S	Mag.+Cryst.		<0.0025
Simpson	74	^{45}Ca	Crystal	16.1(8)	0.008(?)
Chen et al.	75	^{35}S	Magnetic		
Stoeffl & Decman	76	T_2 gas	Magnetic		(in progress)
Kawakami et al.	77	^{63}Ni	Magnetic		<0.00073 95% CL
Norman et al.	78	^{55}Fe (IB)	Crystal		(no effect see.)

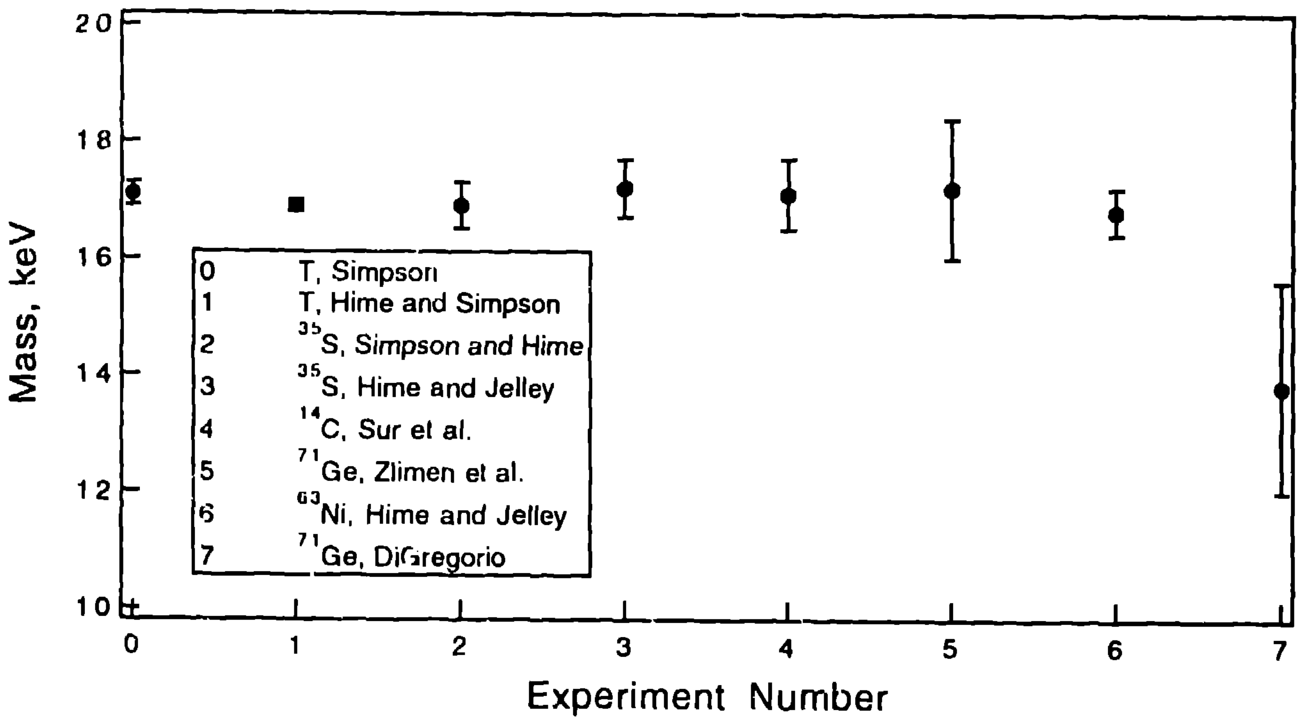

Figure 5. Determinations of the mass of the 17-keV neutrino.

of a thin solid source, a solenoidal magnetic transport, and a silicon detector. With a decreasing field strength along the axis toward the detector, electrons from the source are collimated to a diameter that bears a calculable ratio to the source diameter, without the need for physical collimators that can introduce artifacts into the spectrum. Furthermore, electrons backscattered from the detector are reflected by the magnetic mirror and returned to the detector. Thanks to a geometric efficiency that is essentially 50%, high statistics can be obtained even with very weak (thin) sources, and no arbitrary shape corrections are needed. The ANL group found no evidence for a 17-keV neutrino in ^{35}S decay ($\sin^2\theta <$ 0.25% at 95% CL). To test the validity of their procedures they added a small amount (1.34%) of ^{14}C activity to the source, and could easily observe the artificial kink it produced. The intensity measured was 1.41(9)%, in excellent agreement with the added amount. This is the more impressive given that the distortion introduced in this way is much 'softer' than the sharp kink produced by a massive neutrino.

The Lawrence Berkeley Laboratory group[78] that has reported evidence for a 17-keV neutrino in ^{14}C continues to see the effect, but has now completed a search in ^{55}Fe internal bremsstrahlung emission without finding a positive signal. While less compelling than the two results presented above, this experiment contradicts earlier indications of the effect in this decay mode.

It must be concluded now that the kink reported in many spectra is *not* an intrinsic feature of the electron spectrum and that there is *no 17-keV neutrino*. The observed effects are due to an as yet unidentified cause or causes, and it appears possible that a variety of experimental artifacts may have conspired improbably to reproduce it in so many different situations.

SUMMARY

Direct measurements of the masses of the neutrinos have set upper limits on the masses of

$$\nu_e < 5 \text{ eV},$$

$$\nu_\mu < 500 \text{ keV, and}$$

$$\nu_\tau < 31 \text{ MeV}.$$

In the case of ν_e, the five most recent measurements from tritium beta decay all obtain negative central values for the square of the mass, with a combined significance of 2.3σ. Lacking an explanation for this, the Bayesian upper limit given must be regarded with suspicion. Equally disturbing is the setback in our knowledge of the mass of ν_μ. In the case of stopped π^+ decay, the negative central value for the mass squared is almost certainly connected with theoretical problems in deriving the pion mass.

No terrestrial oscillation experiment now yields evidence for neutrino oscillations, but both the Kamiokande and IMB water Čerenkov detectors show puzzling deficiencies in the muon rates induced by atmospheric neutrinos relative to electron rates. Whether this is due to oscillations, some deficiency in the theoretical interpretation of the production and detection mechanisms, or to some more exotic effect such as proton decay remains an open question. If oscillations are responsible, then parameters in the vicinity of

$$m_x^2 - m_\mu^2 \simeq 10^{-2\pm1} \text{ eV}^2$$

$$\sin^2 2\theta \approx 0.5$$

are indicated.

The deficiency of solar neutrinos seems more and more likely to require neutrino oscillations for its explanation. Matter-enhanced oscillations *à la* Mikheyev, Smirnov, and Wolfenstein explain the data from 4 experiments (Homestake, Kamiokande, SAGE, and Gallex) remarkably well, whereas astrophysical interpretations are increasingly strained. Three isolated regions of parameter space are possible:

$$\Delta m^2 = (0.1 - 1.2) \times 10^{-5} \text{ eV}^2$$

$$\sin^2 2\theta = (0.4 - 6) \times 10^{-2},$$

$$\Delta m^2 = (0.1 - 4) \times 10^{-5} \text{ eV}^2$$

$$\sin^2 2\theta = 0.5 - 0.9,$$

$$\Delta m^2 = (0.5 - 1.1) \times 10^{-10} \text{ eV}^2$$

$$\sin^2 2\theta \geq 0.75.$$

Three new experiments, SNO, SuperKamiokande, and Borexino are expected to provide a definitive conclusion about neutrino oscillations in solar neutrinos.

Remarkable experimental progress has been made on the slowest of natural processes, double beta decay. There are now 6 experimental observations of it, 3 spectroscopic, 2 radiochemical, and one seen both ways. Theory generally accounts well for the rates of the allowed 2ν process increasing confidence in the derived effective Majorana mass, <2±1 eV. All of the spectroscopic measurements of the electron sum energy spectrum in $\beta\beta\nu$ decay show a small but significant excess of counts just below the Q-value. That may be evidence of a Majoron, but further experimental work is required.

The evidence in favor of a 17-keV neutrino has now been convincingly contradicted by new, highly precise experiments. The observed effects appear to be due to some experimental artifacts not yet fully identified.

Physics seems to be at the threshold of a new discovery. All the evidence points to neutrino mass and oscillations as the explanation of the solar neutrino problem. With such a momentous conclusion at stake, the most careful and detailed experimental work is called for, and physicists are heading with enthusiasm to the task ahead.

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